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Environmental Geology

April 27, 1995

Mr. James T. Neal
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Dear Jim:

My sincere appreciation to you for your letter of April 21, 1995 and the reprint for the site characterization paper. It is exactly the kind of article that I would like to present in *Environmental* Geology so that our subscribers around the world would be aware of the site characterization requirements for this type of waste storage.

It was clear that very little work would have to be done for submittal as an article for *Environmental* Geology. My recommendation would be to modify the abstract and perhaps the introduction in a way that would place a greater emphasis on geoscience needed for site characterization for waste management. Perhaps this could be done in the first sentence or two followed by the material you have in the article.

Sincerely yours,

Philip E. LaMoreaux
Editor-in-Chief

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Enclosure: "instructions for authors"

P.S. Bonnie sends her regards to both of you. -

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GEOLOGIC SITE CHARACTERIZATION (GSC) PRINCIPLES DERIVED FROM STORAGE AND MINING PROJECTS IN SALT, WITH APPLICATION TO ENVIRONMENTAL SURETY

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ABSTRACT

The. source of many environmental incidents involving engineered works has been traced (usually after the fact) to inadequate Geologic Site Characterization (GSC). Even though critics may argue that hindsight is almost always clearer than foresight, what is reasonable to some geologists may be overkill to others and GSC is often ***underperformed.*** Communication between designers, geologists, engineers, and regulators is paramount at all stages of a project, each recognizing the essential needs of the other.

For many large projects having substantial longevity, it is essential to periodically review initial conclusions because assumptions and criteria change as the Geosciences evolve, engineering precepts are refined, and analytical capabilities increase. A brief consideration of the changing geological paradigms of the 1950s and 60s as compared with the 1990s should leave little room for debate on this.

Geologic Site Characterization should be a dynamic, continuing ***process,*** not an event. A ***balanced approach*** must be sought, to provide adequate information for safety of operations, neither slighting or overdoing the effort. Several examples are taken fron the salt mining and storage industry which illustrate these principles, but there is widespread application to other geological media and engineering projects. The ultimate benefit of valuing site characterization efforts may be more than just enhanced safety and health-costs not expended in lost facilities and litigation can become profit.

INTRODUCTION

Geologic Site Characterization (GSC) is a necessary prerequisite for the emplacement of storage and mining facilities in salt, but is given unequal attention by different operators. This results from a combination of differences in regulatory requirements, salt environments, and perceptions of what is necessary. The geologic storage of nuclear and toxic waste in salt has distinctive regulatory requirements and is not specifically discussed here, but many of the same principles apply. In fact, the broad principles espoused here apply to most all engineering geology projects having substantial longevity.

Several principles of GSC are reviewed, and some practical suggestions made for implementing them, including periodic updating to ensure currency. Examples have been drawn from from major engineering and mining projects, especially the U. S. Strategic Petroleum Reserve. While geologic conditions are usually slow to change, man's understanding of them is continually evolving and this requires re-evaluation of previous assessments.

GSC RATIONALE

The requirement for GSC has its roots *in personal and environmental safety,* but the principal benefit to the operator ultimately may be *cost savings.* GSC for engineered works must consider the complete range of topics relating to the natural environment, even when thought to be of little concern at specific sites. For most salt storage and mining projects a reasonable *balance of topical detail* must be sought, and GSC activity must proceed in parallel with regulatory and engineering criteria to achieve this. Kiersch (199 1) has shown that as design stages advance from conceptual to detailed, the requirement for specific geotechnical data increases commensurately, at the same time preferred site studies become more focused.

Safety requirements find their expression in engineering design. The Bieniawskis (1994) stressed the interaction that is required between GSC and the engineering design of solution-mined salt caverns, noting in their Principle **#2** that "the best design is one which poses the least uncertainty concerning geologic conditions." Thus GSC data must support the design objectives, *and* be used in the design solution. Understanding *and* effecting this interaction helps to answer the perennial question, "How much GSC is enough?"

Premature judgment regarding site suitability has arisen sometimes when promoters of projects have sought to bring facilities on line as quickly as possible, or when marginal or even defective conditions have existed. While such behavior may be expedient and understandable, it also must be challenged continually, especially involving uncertain conditions having adverse safety or environmental consequences. *Hindsight* often shows that many incidents resulting from incomplete site characterization could have been avoided, had more attention been given to specific topics at the outset.

SALT ENVIRONMENTS

Generalizations about the siting of caverns and mines are difficult, owing to the rich variety of salt depositional environments and structures that exist, even in the United States alone. The following examples show major distinctions, and some types of problems that exist in each. Such becomes the grist for GSC.

***Domal** salt* is perhaps best known because of its association with oil production and extraction of salt and sulphur minerals for more than 100 years. Studies of the more than 250 onshore salt structures in the five sub-basins of the Gulf of Mexico Basin show clearly that none are truly alike. Most show significant differences in origin, size, shape, and features. Yet because of the common derivation from the Louann "mother" salt and analogous diapiric processes, there are also many similarities, at least on a regional scale. In the past 20 years, revolutionary concepts have changed the way geologists regard salt dome processes and structures (Worrall and Snelson, 1989; Jackson and Vendeville, 1994).

For these reasons, the task of GSC must be to identify the distinctions and evaluate them individually within the context of the specific storage or mining project. The very nature of salt diapirism (vertical structures) makes domal salt an inherently different characterization task as compared with bedded salt, but caverns are substantially easier to solution mine. Conventional mining may have fewer differences.

The boundaries between spines or lobes in salt domes imply differential motion between separate units, forming shear or anomalous zones (AZs). These zones have been conceptualized primarily as a result of geologic mapping in underground mines (Kupfer, 1976, 1990, 1995a), but have been difficult to identify in most storage projects where subsurface mapping is derived from geophysics. However, because of difficulty encountered in several projects, concerted characterization efforts to map them may be warranted. More than 1000 caverns have been created for brining and storage in the United States but only a small number have encountered AZs that had significant effects on cavern integrity. On the other hand, underground mines, with much greater horizontal extent, have often been affected in major ways (Kupfer, 1980; Molinda, 1988).

The central **graben** mapped in the **caprock** at Big Hill, Texas, was identified *after* 14 caverns had been constructed for the Strategic Petroleum Reserve (SPR) **(Figure 1).** After the fact it seemed easy to say this marked an AZ, but the experience gained earlier during cavern leaching also showed that anomalous features such as included hydrocarbons, gassy salt, and alkaline brine could be correlated (Neal et al., 1993). Such central **grabens** associated with **AZs** may be commonplace but are difficult to recognize as noted above. Kupfer (1995b) has questioned the association of **grabens** and **AZs**.

Bedded ***salt*** is much more prevalent in area than domal salt **(Figure 2),** but frequently less usable because the shallow deposits have undergone extensive dissolution, and deeper deposits have been deformed or are impractically deep. Market locations and/or transportation access are common logistical constraints for storage and mining. Physical constraints that inhibit development include bed thickness and interbedding of **clastic** units, frequently contributing 25 percent and more of insolubles.

The Upper Silurian Salina group, for example, contains up to 17 individual salt beds, a few of which extend from Michigan to West Virginia. Along the thin western edge of this evaporite basin, salt thickness is primarily determined by filled-in sinkholes or paleokarst topography. Low-angle, gravity-thrust faults (fluid-thrusts: Kupfer, 199%) are observed in deeper salt sections, and true reverse thrusts are found in and best documented in salt mines.

Only the thinner beds still have their original thickness intact over an entire storage or brine field, because salt is always creeping and the rate is proportional to the square of the bed thickness (or diameter).

Dissolution of the salt mass usually begins very early in the history of the salt deposit. The salt is often dissolved around the margins of enclosing reef structures, such as the Niagaran in the Michigan Basin, and the Capitan in the Delaware Basin of New Mexico and West Texas. The salt is sometimes dissolved by seawater soon after deposition and subsequently by groundwater. The fractured reef rocks are more transmissive to groundwater incursion and provide conduits for dissolution.

When markets exist, cavern storage projects have been proposed with as little as 27 m of bedded salt in New York State near an LPG storage facility that thickens in a salt ridge with 60 m of continuous salt.

Such thickening of salt in otherwise uniform, thin beds provides hope for storage in otherwise generally negative environments and is discussed later. At Holbrook, AZ, short and flat LPG caverns were constructed in just 69 m of bedded Supai salt at depths of 305 m below the surface (Figure 3). At Glendale, AZ, much larger, taller and more slender LPG caverns were emplaced at depths of 460-9 15 m because diapiric rise had thickened the deposit. The geologic conditions at Glendale would also be suitable for natural gas storage.

The technology for developing storage in thinly bedded salts is immature in comparison with thicker beds and domes, but many concepts are being considered, including multiple well galleries and horizontal drilling. Cavern development technology in thin beds may be further along than the ability to map the cavems with existing sonar methods.

Salt Anticlines and ridges occur in many bedded salt deposits as a result of arching and/or faulting upward along regional structural trends, often in conjunction with holokinesis. These features are well known in the Paradox Basin of Utah and Colorado and in the Salina Salt in the Michigan and Appalachian Basins of the Northeast. Younger sediments are draped over these structures, commonly forming "piercement" anticlines in the Paradox Basin (Figure 4), and many non-piercement structures in the Michigan and Appalachian Basins. These structures have been perennial targets for oil and gas exploration.

Along the thick eastern edge of the Appalachian Basin, thicker ridges include increasing amounts of shale, similar to the shale sheath found around deep salt domes in the the Paradox Basin and Gulf Coast, around salt ridges and sills.

REGULATORY REQUIREMENTS

The motivation for conducting GSC is obvious for industrial facilities in active seismic areas such as California or Japan, especially for high risk activities such as nuclear power plants where regulatory proscriptions are formidable. For Gulf Coast storage and mining there are entirely different natural threats and the approach is generally much less rigorous, at least regarding seismicity. Thus, engineering judgment and common sense must dictate what level of GSC is needed for specific applications, and most often history is our guide. However, we suspect that history is often soon forgotten and its lessons must be relearned.

Engineers prefer not to overdesign for reasons of cost, but neither is it desirable to *underestimate* requirements, as costly retrofits (even if possible) may become necessary. Seismic hardening in earthquake zones is a case in point, which after the fact, can be a difficult engineering challenge. Unfortunately, with storage caverns in salt, there are practical limits to what can be done to alter mistakes made during the initial emplacement.

Salt storage projects in Arizona, Louisiana, Mississippi, and Texas are regulated by similar and yet distinctive rules within each State. They differ for a variety of reasons. A characteristic of all is that they abhor specificity, and rely on *demonstrating* essential safety of proposed projects through the mechanism of hearings that are backed up by voluminous study documents--often produced by consultants. There is generally little proscription that limits specific conditions, and exceptions are allowed, again based on reasonable demonstration. The broad nature of salt environments discussed earlier is perhaps the principal reason for limiting specificity. Also, Kupfer (1995; private communication) has noted an analogy with the U. S. Constitution, in that a general statement of principles averts frequent amendments. The system has generally worked well, and a few leading firms in the industry have enjoyed preeminence over the years. However, some rethinking on regulatory definition may be in order.

The range of geotechnical topics requiring consideration is outlined in Table 1. The emphasis to be placed on specific subject matter must be gained from experience and engineering judgment. There have been few attempts to specify the range of geologic topics required in permitting other than the Canadian standard for storage of hydrocarbons in underground formations (Canadian Standards Association, 1993).

Within Texas, sufficient variability exists from east to west that some geologic processes and events are quite different. Groundwater may be at the surface near the Louisiana border but much deeper in the High Plains on the New Mexico side, making requirements for deterring hydrocarbon leakage different in each environment. Both raw water and brine disposal are critical in the arid west, with vastly different hydrology. Such variability makes the task difficult for the regulator, but supports the concept of site-specific permitting.

And even though Federal, state, and local regulations dictate what types of studies must be accomplished for various types of projects, *usually there is no requirement to reevaluate the initial conclusions.* All too often that happens only after trouble is experienced, and even then receives analysis only during accident investigations. The U. S. Department of Energy (DOE) now requires natural phenomena hazard assessments as a matter of course, *and* requires updates at 10 year intervals, or as otherwise indicated (DOE, 1993; 5480.28). GSC updating was anticipated in the early days of the SPR program, even before the subsequent DOE requirement. The remaining discussion makes a case for continuing, periodic updates to GSC.

EVOLVING CHARACTERIZATION TECHNOLOGY

In addition to the evolving conceptual understanding of salt deposits and processes, means of study have changed, in turn contributing to conceptual advancement. The ability to obtain quality geological data, especially from geophysical exploration, has improved markedly in the past 20 years and this has significantly aided more accurate GSC for cavern storage, but at increased cost. For example, 3-D reflection seismic methods have revolutionized the geologic picture offshore. Onshore, vertical seismic profiling **(VSP)** and salt proximity surveying, combined with precision directional drilling, have provided a more detailed view of many dome edges, High resolution profiling over **the** tops of domes such as Stratton Ridge, TX, has shown detailed structure previously little known. The Big Hill map **(Figure** 1) was produced by modem seismic reflection profiling. It differs significantly from the earlier interpretation, and is causing rethinking about anomalous zones in salt (Magorian et al., 1993). This in turn may affect our decisions about how and where we store crude oil in our national SPR, or other products elsewhere.

The top of Boling Dome, TX, was recently mapped by 3-D seismic reflection as part of the **characterization** necessary to develop toxic-waste storage caverns next to the Valero gas storage facility. The profiles revealed abrupt ledges which may be related to **AZs**. An off-dome 3-D layout failed to find a turning wave from the steep flank. However, reprocessing of previous 2-D data, stacking only from the outside, solved the problem.

Napoleonville Dome, LA, has been studied seismically as well, in an attempt to position additional caverns between complex brine galleries. The top of salt is relatively flat, apparently due to an active water drive in the river-levee point bars overlying the **caprock,** The overhang on the south side again could not be resolved with the same approach. A much more satisfactory resolution of a flank overhang was developed at Jennings Dome near Evangeline, LA, by piggy-backing closer-spaced data on a conventional **2-**D seismic regional group shoot. By stacking the data only from the outside, it was possible to define the overhang depth within 15 m.

This improved quality of information allows engineering judgement to be less constrained by uncertainty, which in the past led to overconservatism. Thus, the caution that was previously factored into some storage decisions can now be lessened, and with equal or greater degrees of safety.

SOME HARD-LEARNED LESSONS FROM STORAGE AND MINING PROJECTS IN SALT

Bayou Choctaw Cavern 7 (uncontrolled leaching)

At Bayou Choctaw salt dome near Baton Rouge, Lousiana, which presently contains 52 million barrels of SPR crude, an 245 m diameter lake formed in 1954 when the overburden over a brining cavern collapsed into the brine cavern below. With the advent of sonar surveying and controlled leaching, it is unlikely that such mistakes due to uncontrolled brining through the caprock would be repeated today (Neal et al., 1993). But even today, additional questions relative to the cause have arisen because of the peripheral location on the dome and likely faults in the caprock. The possibility of a similar collapse at nearby Cavem 4 has been evaluated on several occasions but is presently thought to be unlikely.

Weeks Island, Louisiana, Strategic Petroleum Reserve Site (sinkholes / storage in mines)

A sinkhole at Weeks Island formed in 1990-91 over the edge of the mine as a result of geological, hydrological, and mine-induced factors. The location near the edge of the dome, astride a possible anomalous zone (AZ), set the stage for the mine configuration, following essentially natural boundaries created by geologic features. The AZ designation seems appropriate as black salt, blowouts, brine seeps, shearing, and a salt valley were identified even before the oil emplacement. Such anomalous features when occurring in multiples were subsequently conceptualized to comprise the salient elements of AZs, (Kupfer, 1990; Neal, 1995) A second and smaller sinkhole was discovered in early 1995 over the edge of the mine, and in a trough between two areas of higher salt, possibly separating individual lobes or spines.

Mine geometry and excavation-induced stresses placed the mine periphery in tension, probably favoring crack development as early as 1970 (Ehgartner, 1993). Eventual incursion of undersaturated ground water traversed the 107 m salt back over the mine, allowing entry of brine into the SPR mine. Gradually increasing dissolution enlarged a void at the top of salt, creating the collapse environment for the sinkhole that formed circa 1990-91. Exploratory drilling and geophysics defined the void or crevasse beneath the sinkhole, enabling the introduction of saturated brine directly into the throat. The brine essentially arrested the continuing subsidence at the sinkhole, apparently as a result of controlling ongoing dissolution. Additional drilling diagnostics and hydrologic analyses determined that mitigation could be achieved by constructing a freeze wall around the sinkhole to effect groundwater control, prior to relocating oil from the mine (Neal and Myers, 1995).

The lesson learned here is that storage of hydrocarbon products in room and pillar mines can involve substantial cost, based on experience with sinkhole formation in at least six other Gulf Coast mines. The inability to perform maintenance grouting from within the oil storage facility was the primary detriment not forseen at the outset. The importance of mine-induced factors in localizing sinkhole occurrence is also noted, along with. geologic features, especially AZs.

Strategic Petroleum Reserve gassy oil (AZs / gas in salt)

In early 1993 it was learned that a number of caverns within the SPR system had accumulated excessive amounts of gaseous hydrocarbons which were dissolved in the oil. The oil would require degassing prior to refining in many cases, and because the processing rate may be less than the drawdown rate criteria, cycling of oil and concomitant degassing is anticipated in order to maintain drawdown readiness [Oil and Gas Journal, 1993, 1994]. A related problem involves the geothermal heating of stored oil, which exacerbates the problem of gassy oil.

In a number of instances the gas content had increased, leading to the conclusion that the source originated from within the salt (Hinkebein, et al., 1994). Gas in salt has long been a problem in conventional mining, leading to several fatal accidents following outbursts of gas and associated saltfalls (Mohnda, 1988). At Bayou Choctaw SPR Site, Caverns 18 and 20 showed higher than allowable gas content in March and May, 1993, and were identified as requiring treatment prior to drawdown. A possible correlation of gassy caverns and a shear zone trending N 75° E that transects the dome may exist; a similar N 45° W shear zone occurs at Bryan Mound, Texas (Thoms, 1993). The apparent correlation with the *anomalous zone* (AZ) at Bayou Choctaw may be similar to that noted by Iannacchione et al. (1984) in his study of gas associated with salt outbursts in conventional mining. This correlation suggests that gas migrates through these AZs and into the adjacent salt at a faster rate than in normal salt. At Bayou Choctaw Caverns 18 and 20 are evidently in the salt adjacent to the AZ (Figure 5).

The lesson here is that hydrocarbon storage requires thorough evaluation of salt properties, which includes intensive exploratory drilling and laboratory analysis. Special attention to location near AZs is required.

Napoleonville and Clovelly (Insufficient characterization; inadequate buffers)

Reports of cavern integrity and pressure maintenance problems at these domes are known for some caverns placed near salt stock edges, resulting in the inability to use certain caverns. At Clovelly it appears that a cavern placed too near (or in) the salt overhang may be in salt that is inferior as a result of inadequate buffer **(Figure 6). Each** cavern was leached through five large-diameter calyx holes without logged pilot holes, precluding detailed salt examination during development. The original design may have assumed a more conical salt stock, perhaps being unaware of a large assymetry in the **gravity** anomaly and associated well control. At Napoleonville shale layers were encountered in at least one brine cavern **(Figure 7),** indicating that the salt edge margin probably had been penetrated and that inadequate buffer existed. A similar encounter with shale was noted at Bayou Choctaw in a brine cavern.

The lesson here is that inadequate buffers can be costly, but that with more concerted characterization effort, some should be avoidable. However, in some cases of legitimate uncertainty or insufficient data, trial and error may be necessary prior to cavern emplacement.

The Jefferson Island, LA, mine flooding incident in 1980 **(Thoms,** 1994) has been attributed more to location error than to a GSC insufficiency. However, it points out in general the necessity of map accuracy for all features, both natural and cultural, in GSC products. **The** 1994-5 flooding **in the Retsof Mine, NY,** occurred in bedded Salina salt and bears little resemblance to Jefferson Island. The formation of major surface effects, large including cracks and subsidence sinks, occurred subsequent to massive water influx following a Magnitude -3.5 seismic event on March 12, 1994 [Thompson, S. N., **1994]**. The seismicity was subsequently shown to the result of the mine collapsing. The cause of this mine collapse is currently centering on yield-pillar mine design, the high horizontal stress regime, and on geologic irregularities of buried valley structures (Young and Nieto, 1995). Because this salt mine was the largest in North America and supplied a substantial amount of road salt each year, the mine failure has attracted much attention. The widespread surface effects have prompted litigation of major proportions from local residents.

Lessons learned at Retsof are only beginning to be understood from a geotechnical perspective but are sure to be the subject of many articles for years to come. The cost of such incidents, not only **monitar**ily but in human resources, is immense. Unanticipated events such as these are usually explainable in *hindsight.* Our goal in planning storage and mining projects should be to understand their causes sufficiently well so as to avoid them in the future. Thus, a principal function of GSC is to anticipate where such dissolution and subsidence events are possible, and to make appropriate precautionary caveats in the siting of facilities.

PERIODIC UPDATE REQUIREMENTS

The active life of solution mined storage caverns for liquid and/or gaseous hydrocarbon storage can extend for 40 years or more, as has been demonstrated at many domes. In fact, some brine caverns are now more than 50 years old. This longevity is such that continual updating of the geological data base is essential. The conceptual understanding of salt dome processes and features is evolutionary and may change the way in which we think about a particular problem or site. And some geologic processes are sufficiently active that significant changes can occur within the life of a storage project and affect storage integrity.

We do not normally expect dramatic changes in our knowledge base, and yet it is necessary to realize geology is a young science that is changing and evolving at a rapid pace---sometimes faster than we can assimilate. Plate tectonic concepts, unspoken in many circles just 30 years ago, are still evolving, and new paradigms about salt flow tectonics that are perhaps equally revolutionary are occurring now and causing us to alter our traditional ways of thinking about things. All of this indirectly affects how we think about engineering applications, such as cavern storage projects.

Anomalous zones (AZs) are deviations from pure salt and may be common features to almost all domes, but they were not fully recognized and conceptualized until the last 20 years or so (Talbot and Jackson, 1987; Kupfer, 1989, 1990). They have been shown to affect cavern shape, and at some sites the storage operations-for several reasons. In many cases hindsight is required, where new information or understanding must be applied to existing facilities. Big Hill and Bryan Mound, TX, and Weeks Island, West Hackberry, and Bayou Choctaw, LA, are Strategic Petroleum Reserve sites which now reveal more complete geologic understanding than was available at the time the facilities were first instituted (Magorian, Neal, various). The periodic updates conducted at these sites have provided added confidence for continued safe storage of crude oil.

Caverns undergo shape changes because of salt creep closure, but especially when products are cycled and fresh or brackish water is introduced to displace products. Cavern enlargement thus occurs and sometimes overlying caprock is also involved. The continuing appraisal of safety margins based on salt thickness and dome shape are required and this may evolve along with dome understanding. The experience of SPR at Bayou Choctaw, LA, shows that periodic updating and monitoring of Caverns 4, 20, and **15/17** are essential to ensure cavern integrity and site safety because they were somewhat marginal at the outset.

Subsidence monitoring of all SPR sites has been accomplished at least annually and shown significant variation in amount from site to site. Part of the variation is caused by regional differences in the settling of the coastal plain sediments, but some is due to the nature of salt properties or other dome-specific features. West Hackberry is an example of extensive, major subsidence caused by multiple sources, in addition to the primary cause in cavern creep closure (Neal and Magorian, 1993). Some of the 25 cm of subsidence that occurred between 1987 and 1992 was caused by local and regional effects, but much of it results from salt creep closure of the SPR storage caverns below. This rapid rate is of concern where **well**head elevations are already near sea level. Continuing surveillance and reappraisal is clearly indicated. However, the understanding of the causes, rates, and magnitudes of the subsidence allows site operations to continue without apprehension.

Dome shape and associated structure does not change, but the availability and quality of logs from adjacent well fields has modified our *interpretation* at several domes. And with new interpretations of salt contours, our estimates of salt edge-to-cavern safety buffers has changed-by 150 m and more for some SPR caverns at Bryan Mound, TX (Neal and Magorian, 1994).

Risk analysis of other geotechnical hazards must be continuously updated as new and refined information is made available. In this regard, earthquake, hurricane, and flooding potential are better understood from a threat and warning viewpoint than they were 15 years ago. This new information enables improved advance planning and emergency preparedness.

The update interval will depend on many factors, highly variable in every situation. Experience gained from the U. S. Strategic Petroleum Reserve may be applicable for other storage and mining projects, some of which have made no attempt to systematically upgrade the initial geological site characterization reports, even when knowledge about some features or processes had evolved.

The simple facts are that operations change, geologists come and go, and things happen (to paraphrase one bumper sticker). And so it is no wonder that when we review reports that were written 15-20 years ago (and sometimes even less) we are aghast at some notions. Geology usually doesn't change much in a few years, but our understanding of major concepts evolves and this is reflected in the details of our site reports. It is common knowledge that *credibility **and** authority **change**—***sometimes **slowly,** and sometimes virtually overnight. This usually goes hand-in-glove with changes in conceptual knowledge.

How does one plan for all of this at ***the outset?*** We should acknowledge our **soft** spots up front. This may be easier said than done, but with honest self-appraisal we should at the least tentatively plan when updates are apt to be needed and how they could affect the system in question. But without resource planning it simply won't happen.

CONCLUSIONS:

Caverns in salt are a very valuable resource, and in some locations a rare commodity because of limited salt availability. As such the GSC activities associated with them become a dollars and cents proposition. In all cases they require adequate characterization for health, safety, and environmental protection. If these requirements are not properly addressed, the result may lead to loss of facilities and even costly litigation.

To be effective, GSC must be proceed in parallel with engineering design objectives-at each stage in the design process, becoming progressively more detailed and firm. Those involved with these functions should have a clear understanding of the respective needs and data requirements of each other.

Geologic site characterization should be an ongoing <u>process,</u> not an <u>event!</u> *The task of site characterization must not stop after the initial effort and needs to be revisited every so often.* Regulatory requirements for GSC should include provisions for periodic updating at least every 10 years, and more frequently for some types of projects.

We must recognize change:

- **Events** in the form of natural proceses never stop, and are frequently unpredictable.
- **Man's actions** can change many things, often unwittingly, and sometimes with quite unexpected results.
- **Geoconcepts** evolve, leaving some earlier interpretations in doubt, but also preparing the way for a new generation of geoscientists who surely will make much current geothinking obsolescent.

- **Authority** evolves with each new generation of geoscientists and knowledge, in parallel with concepual advancements.
- **Tools improve.** Data gathering and information processing surely will continue to improve, especially in geophysics.

Apply Specifics; Adjust Risk /Safety Evaluations: All of this modified information base is required to revise the interpretation of safety and risk analyses.

At the outset of projects, the following aspects should be recognized explicitly as part of GSC reports:

- **Quality, Uncertainty (in data** base)
- **Update Recurrence Interval** should be scheduled in advance (10 yr minimum)
- **Budget Planning** (essential for update)

Just a few examples of change have shown that GSC updates are important Events happen—no doubt about it! Some could have been avoided, had more attention been given to GSC up front. These principles relate to virtually all varieties of geologic environments, not restricted to salt, such as the examples of this paper. Finally, GSC is a two-way street; information gained from storage and mining projects has helped advance the state of knowledge in the Geosciences, making it a cooperative venture that provides benefits to both.

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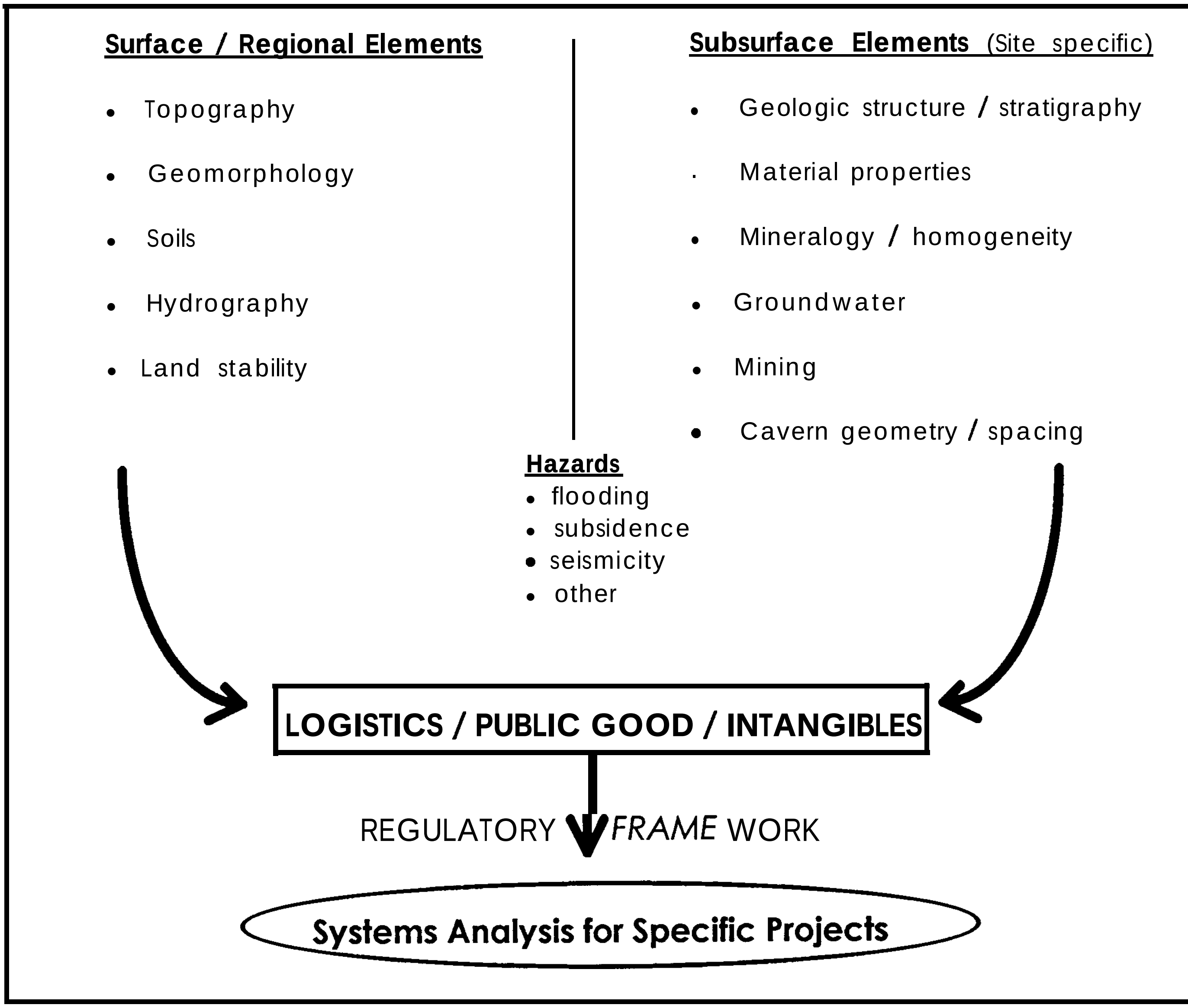


Table 1 Generalized Outline of Principle Elements of Geologic Site Characterization (GSC) for Storage and Mining Projects. The product of GSC is incorporated into regulatory applications and for systems analysis, which is not part of the geological report.

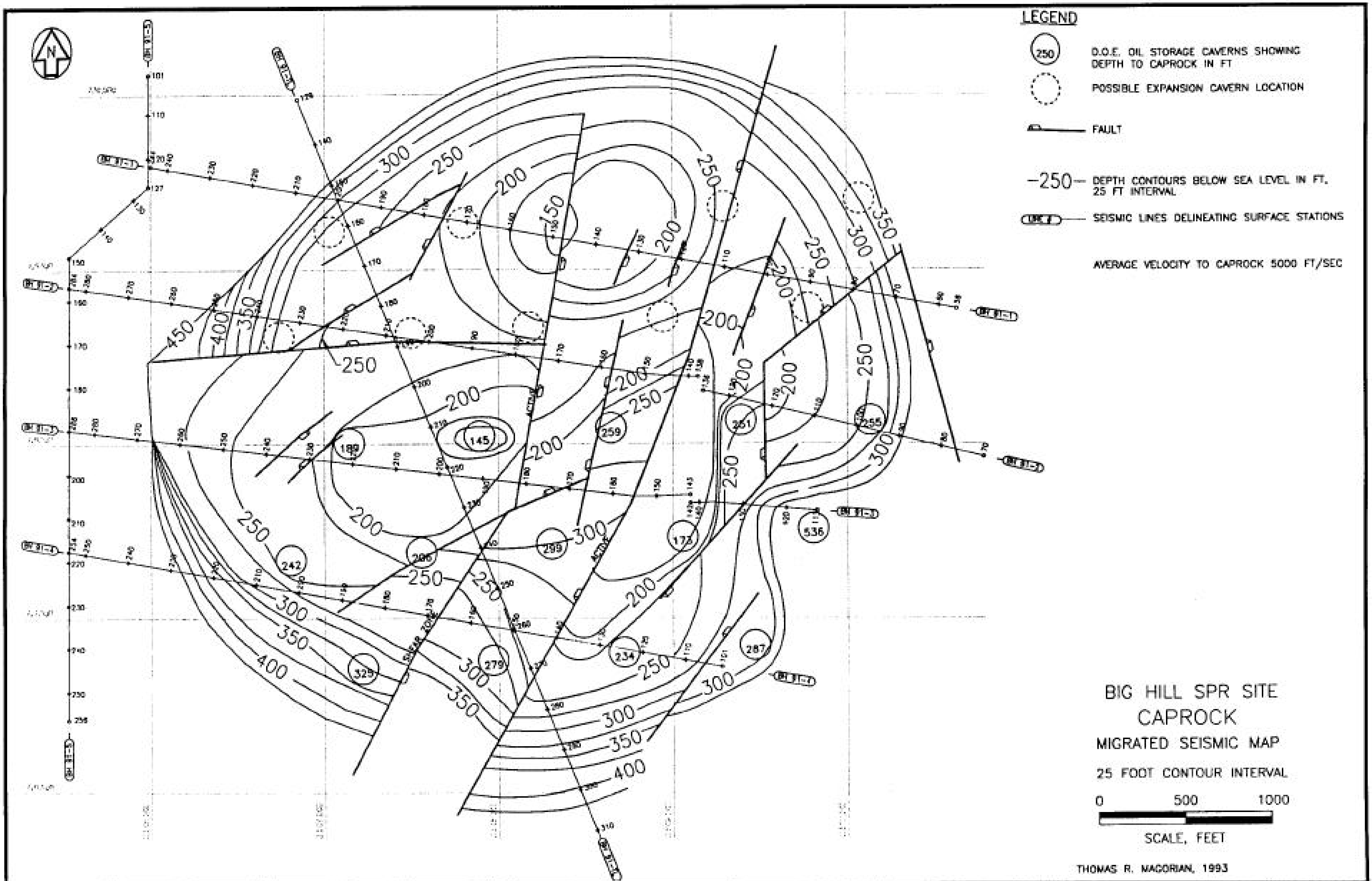


Figure 1 Map of caprock at Big Hill salt dome, TX. Contours obtined fron reflection seismic profiling and numeous wells. The central graben manifested in the caprock may be substantially wider than the AZ in the underlying salt.

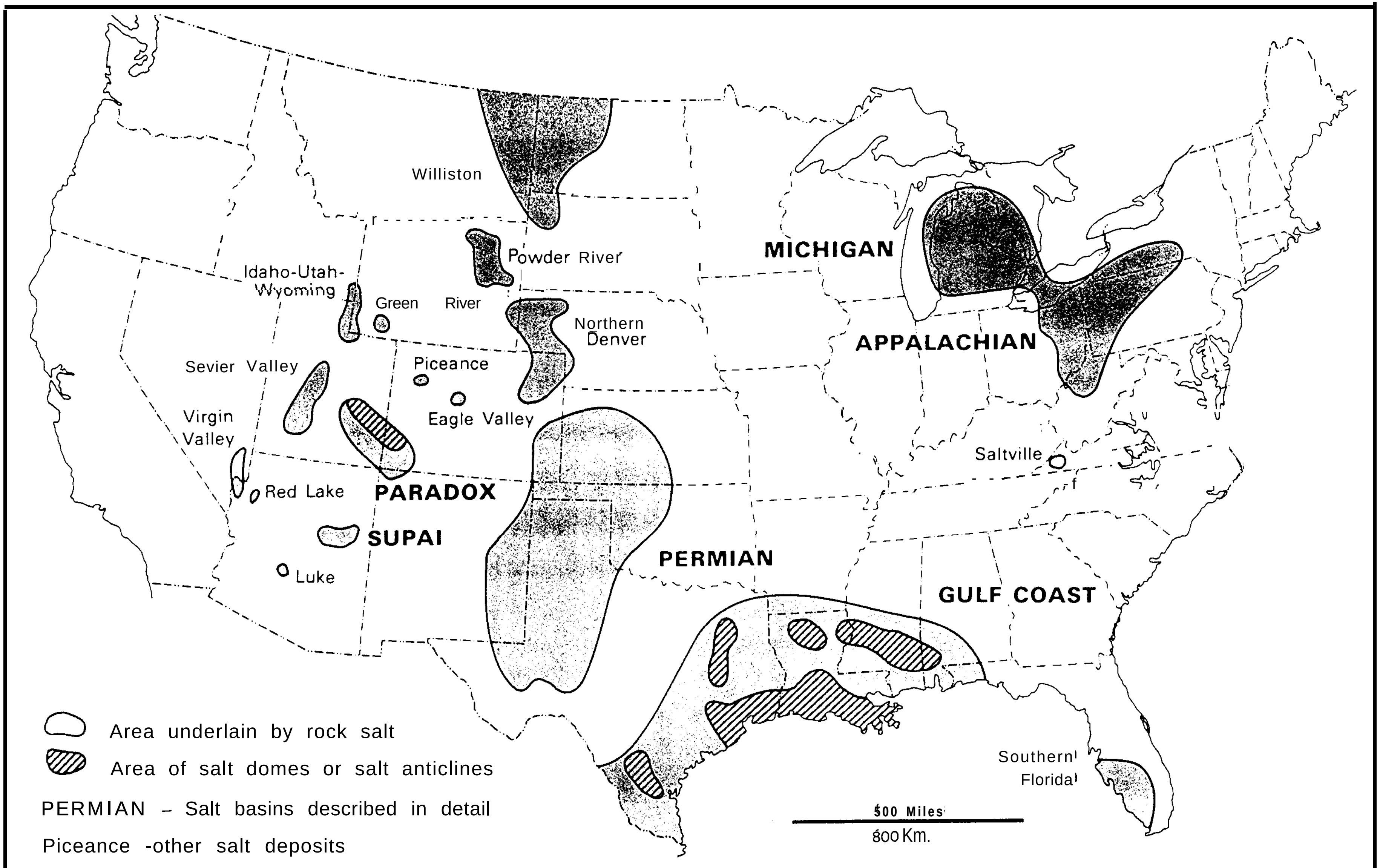


Figure 2 Map of principal rock-salt deposits in the United States (from Johnson and Gonzalez, 1978).

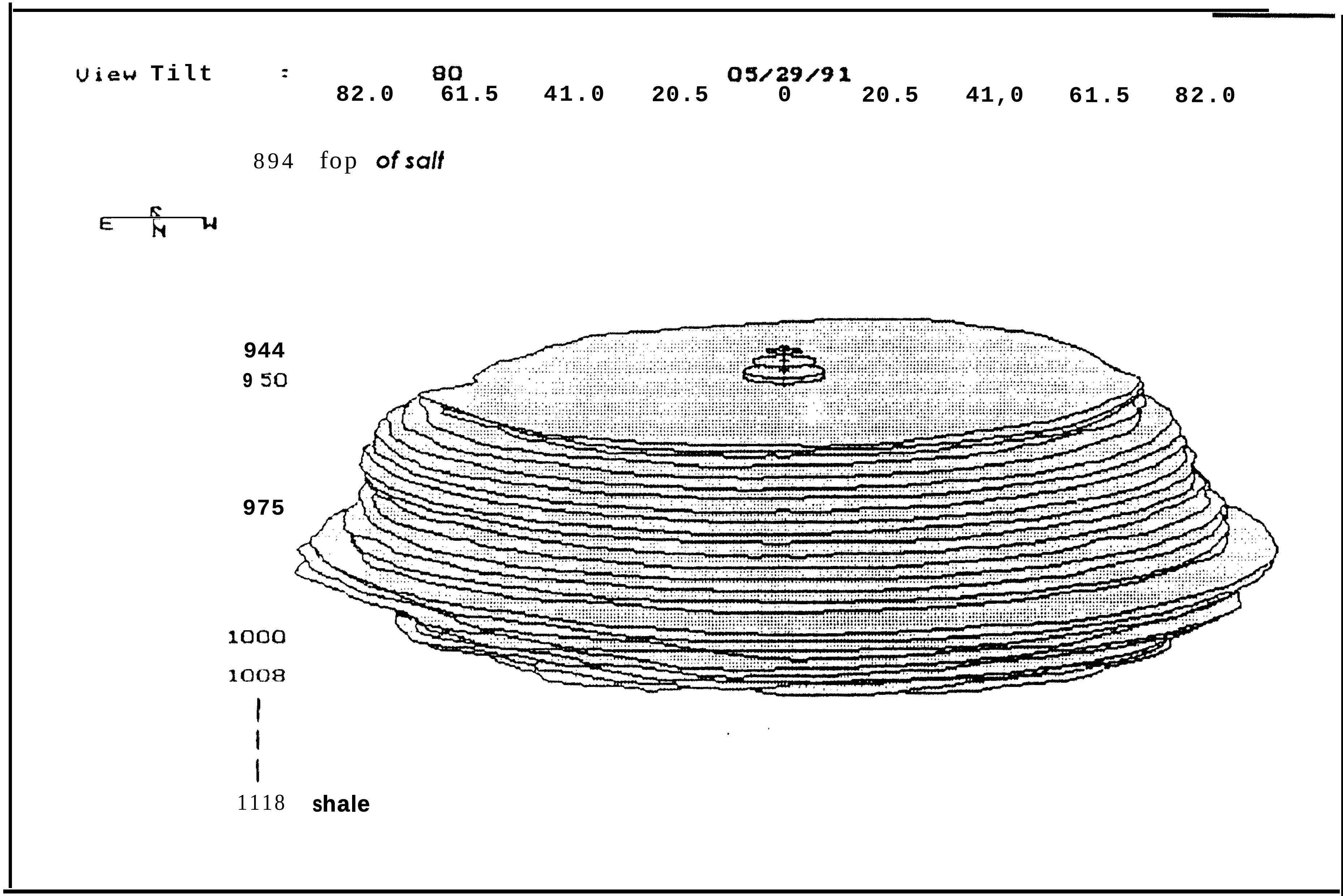
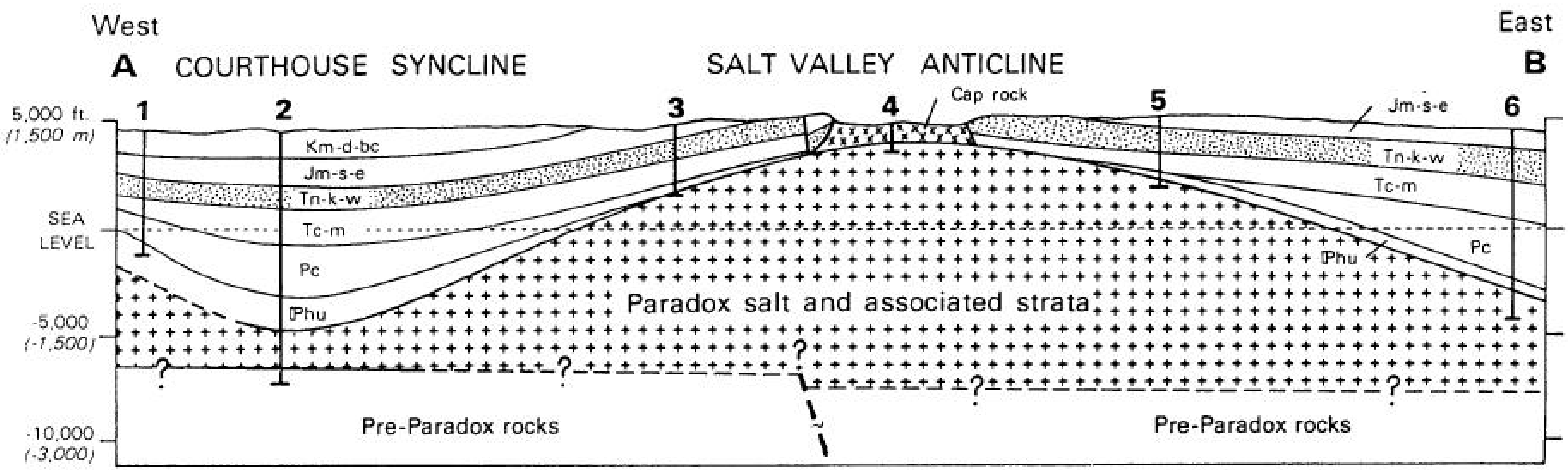


Figure 3 Caverns in Arizona's Supai Salt Basin require short, squat configurations for LPG caverns at Adamana, AZ. Sonar survey of Ferrelgas Cavern 3 reveals cavern height of 164 ft in salt section of 224 ft.



WELLS USED IN SECTION

1. Equity, Donahue No. 1
2. Texaco, McKinnon No. 1
3. Continental, Gov't.—Hall No. 1
4. Western Allies
5. Pure, Salt Valley No. 1
6. Union, Devils Garden—USA No. 1

Km-d-bc	Mancos-Dakota-Buro Canyon
Jm-s-e	Morrison-Summerville-Entrada
Tn-k-w	Navajo-Kayenta-Wingate
Tc-m	Chinle-Moenkopi
Pc	Cutler
IPhu	Hermosa (Upper Member)

Figure 4 Cross section through Salt Valley piercement anticline in Grand County, Utah (modified from Hite and Lohman, 1973). Excess salt beneath anticline is problematic and should be regarded as diagrammatic rather than actual. From Johnson and Gonzales, 1978.

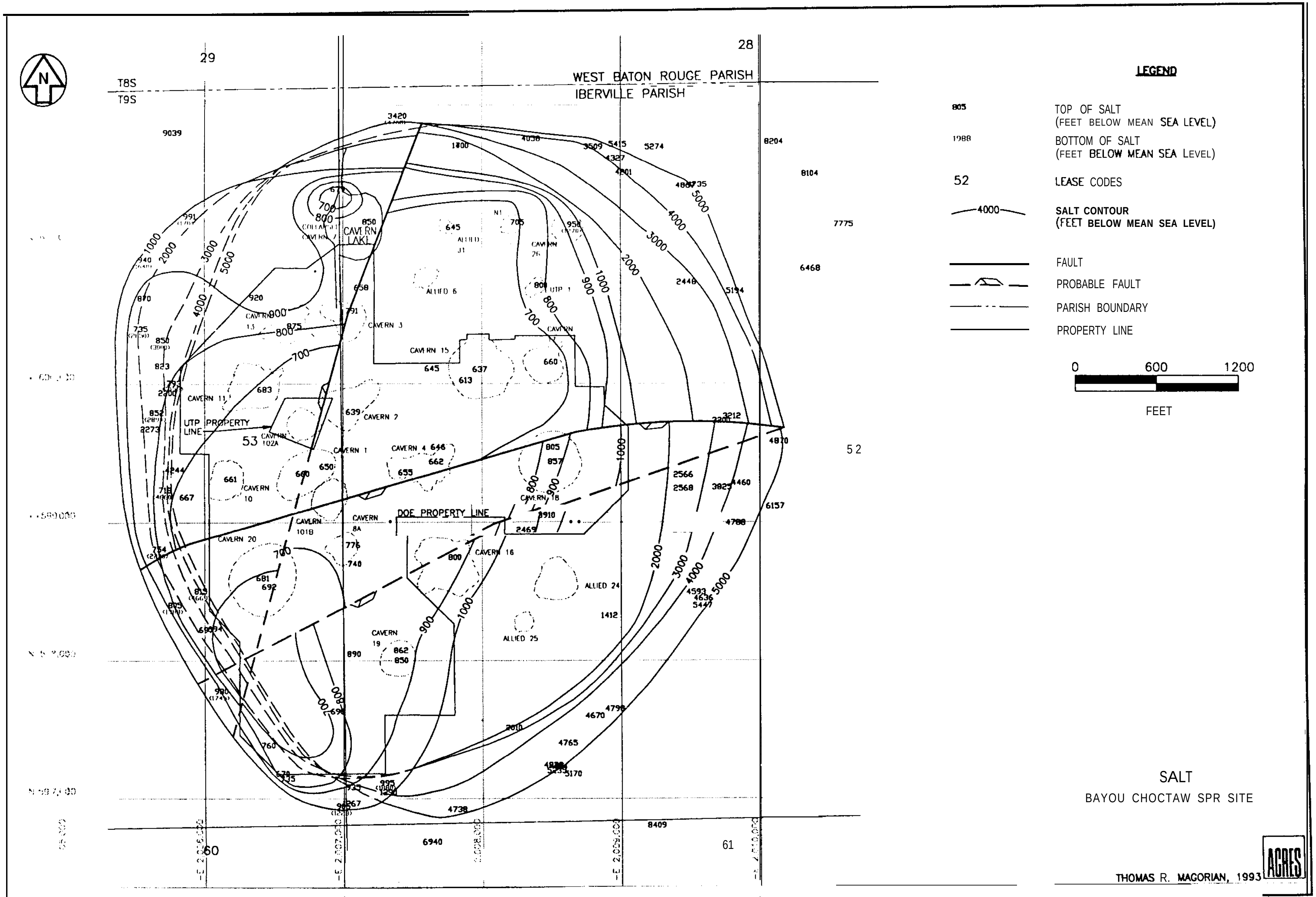


Figure 5 Shear or anomalous zone (AZ) transects entire salt stock at Bayou Choctaw, Louisiana, salt dome. Strategic Petroleum Reserve Caverns 18 and 20 contain excessive gas, possibly related to their position astride the AZ.

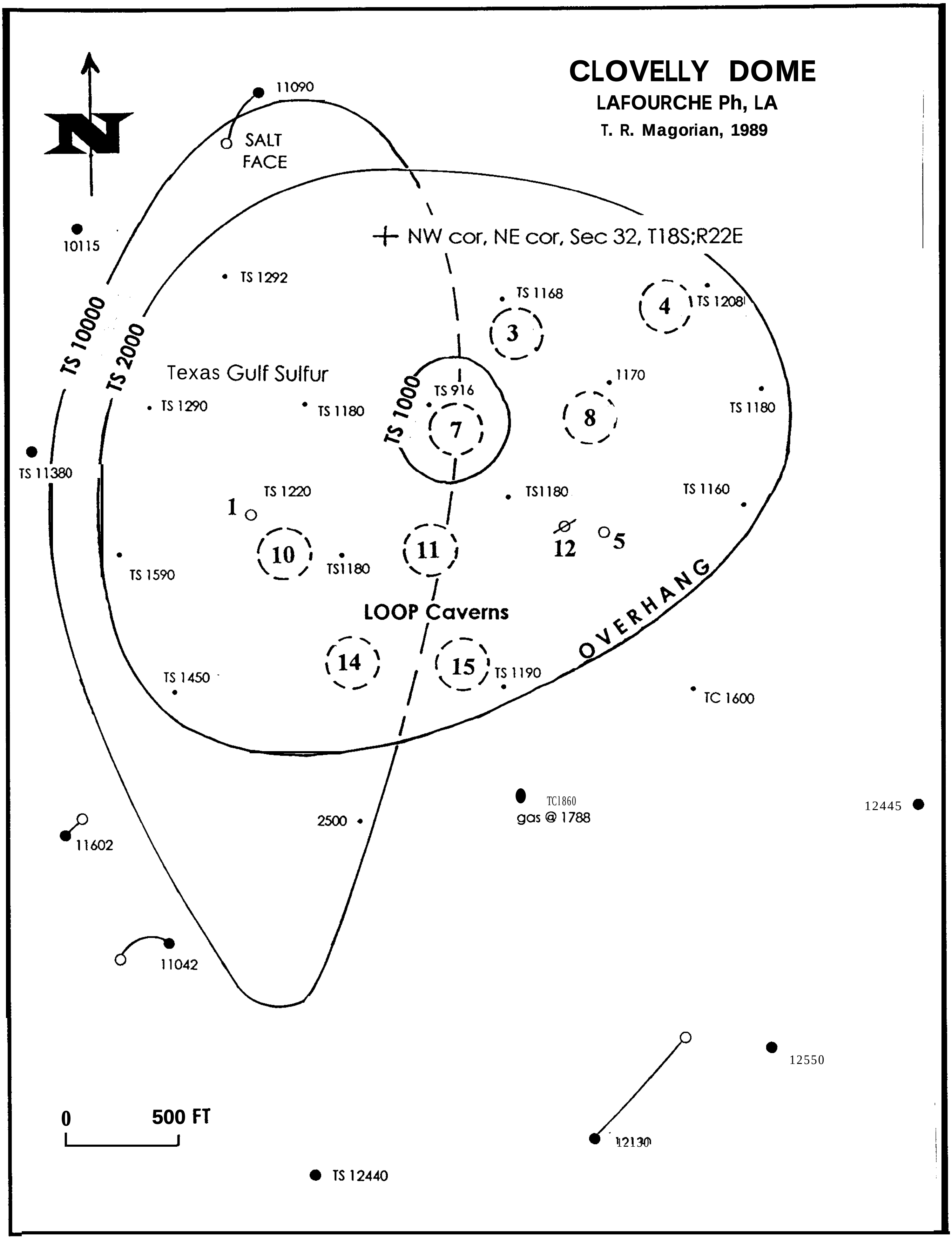


Figure 6 Salt Contours at -1000, 2000, and 10,000 feet, showing overhang on east side of Clovelly Dome. Teardrop shape of salt stock apparently has resulted in marginal space in overhang,. The authors' interpretation of asymmetric gravity contours suggested a tilt in the salt stock, although an unverified AZ could also influence salt purity, according to the operator. Map is sketch representation.

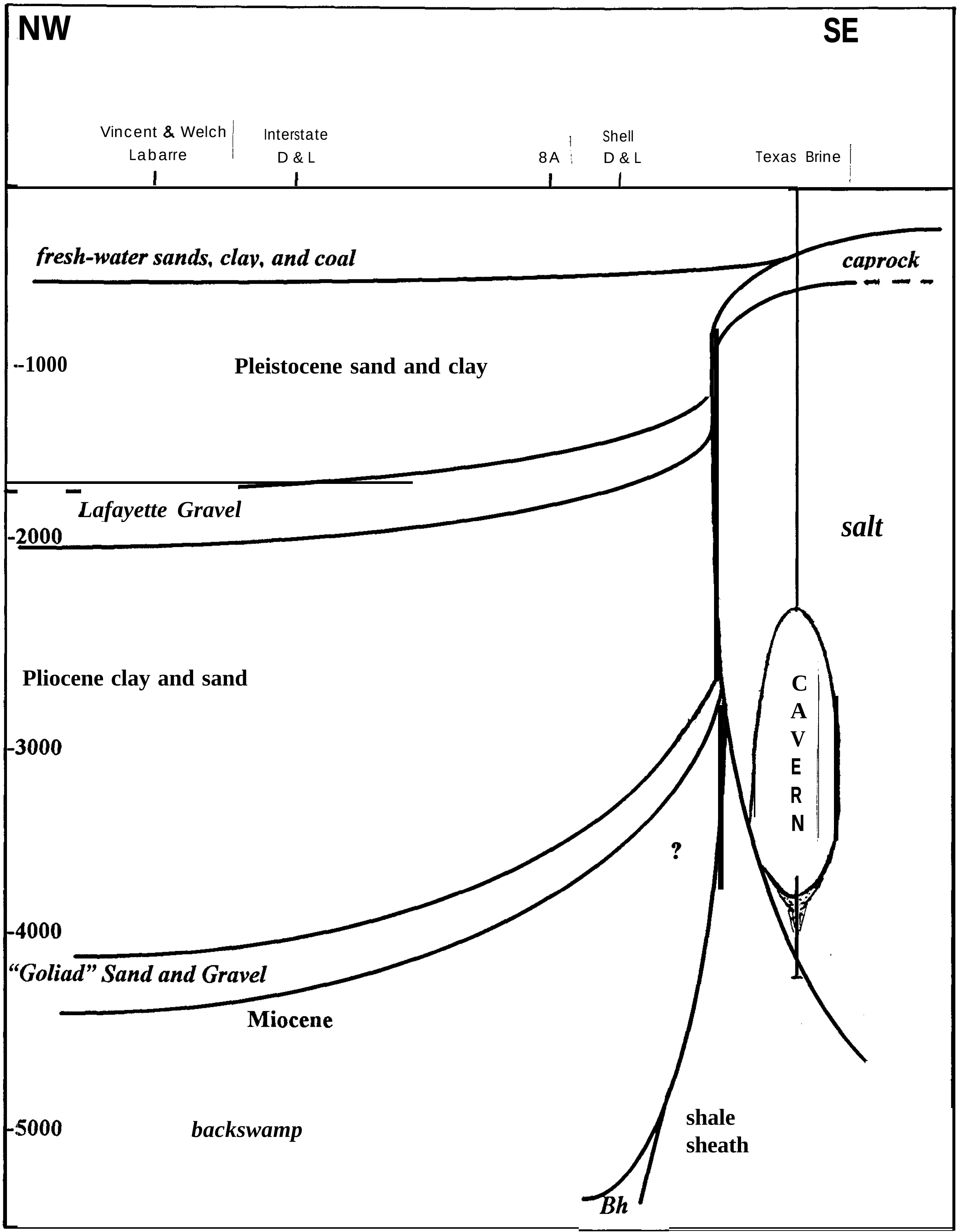


Figure 7 Conceptual diagram of westernmost cavern on Napoleonville dome, showing the penetration of the salt stock into the overhang. Because of the fortuitous presence of shale sheath, this cavern was not lost, but easily might have been.